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Squeezing of Cavity Fields in Cascade Multiphoton Processes

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Squeezing of cavity fields in cascade multiphoton processes

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Abstract

For a system of a multilevel atom interacting with a single-mode cavity field, squeezing of the field is studied numerically. It is found that the squeezing effect becomes stronger when the atomic level number increases, but tends to saturate when the number exceeds twenty.

I. Introduction

The interaction of an atom with cavity fields has stimulated great interest because many interesting and novel phenomena have been discovered. In addition to quantum collapse and revival (Eberly et al 1980), the atomic-field system has been shown to exhibit a subPoissonian photon distribution (Puri and Agarwa 1986), squeezing (Meystre and Zubairy 1982) and stationary atomic inversion (Savage 1988). Recently, Li and Zhu (1985) and Kozierowski (1986) studied the dynamics of an M-level (M-1)-mode system with the atom having a common upper level. Most recently, the present authors (Li et al 1989) examined the effects of the atomic level number on quantum collapse and revival and photon statistical properties in the interaction of a multilevel cascade atom with single-mode cavity field. In the present paper we study squeezing effects for an M-level atom interacting with a single-mode cavity field. First we present the formalism for the problem. Then we proceed to study fluctuations of the field mode and examine effects of the degenerate multiphoton processes.

II. Formulation

We consider a cascade atom with M energy levels as shown in Fig. 1. The total Hamiltonian is, in the rotating-wave approximation,

$$H = \hbar\Omega a^{\dagger}a + \sum_{i=1}^{M} \hbar\omega_i A_i^{\dagger}A_i + \sum_{i=1}^{M-1} \lambda_i A_{i+1}^{\dagger}A_i a + \text{h.c.} \quad , \tag{1}$$

where the operator $a^{\dagger}$ creates a photon, $A_i^{\dagger}$ creates an atom in the i-th level, and λ_i are the atom-field coupling constants. Our discussion will be limited,

for simplicity, to processes involving only a single-photon transition between adjacent atomic levels.

We define the total excitation number operator as (Li et al 1989)

$$\hat{N} = a^{\dagger}a + \sum_{i=1}^{M} iA_i^{\dagger}A_i \quad , \tag{2}$$

which is the sum of the photon number and atomic excitation number operators. It can readily be verified that $[H,\hat{N}] = 0$, i.e., $\hat{N}$ is a constant of motion. If we are only interested in the particular case in which the atom is initially in its higher level, then we need only consider that part of the Hilbert space involving state vectors corresponding to $N \geq M$, where N is the eigenvalue of the operator $\hat{N}$. This is a consequence of the fact that N is a conserved quantity.

Consider the state

$$|i,n\rangle = |i\rangle|n\rangle \tag{3}$$

in which there are n photons in the field and the atom is in the i-th state. The subspace corresponding to $N = M + n$ is spanned by the state vectors $|M,n\rangle$, $|M-1,n+1\rangle, \ldots, |i,n+M-i\rangle, \ldots, |1,n+M-1\rangle$, where n is the photon number in the field and can take any positive integer value. Since state vectors in different subspaces are necessarily orthogonal, the total Hamiltonian can be diagonalized in every subspace.

An arbitrary state in the subspace corresponding to N can be expressed as

$$|\phi_n\rangle = \sum_{i=1}^{M} C_{i,n+M-i}|i,n+M-i\rangle \quad , \tag{4}$$

where the expansion coefficients $C_{i,n+M-i}$ satisfy the stationary-state Schrödinger equation

$$\sum_{i'=1}^{M} (H_{ii}\delta_{ii'} + H_{ii'} - E\delta_{ii'})C_{i',n+M-i'} = 0 \quad . \tag{5}$$

The matrix elements in (5) are given by

$$H_{ii} = \langle i,n+M-i|H|i,n+M-i\rangle = (n+M-1)\hbar\Omega + \hbar\omega_1 - \sum_{j=1}^{i-1} \Delta_j \tag{5a}$$

$$H_{ii'} = \langle i,n+M-i|H|i',n+M-i'\rangle$$

$$= \lambda_{i'}\sqrt{n+M-i'}\,\delta_{i,i'+1} + \lambda_{i'-1}\sqrt{n+M-i'+1}\,\delta_{i,i'-1} \quad , \qquad i \neq i' \quad . \tag{5b}$$

Here we have defined the detuning parameters

$$\Delta_i = \hbar\Omega - \hbar(\omega_{i+1} - \omega_i) \quad , \qquad i = 1, 2, \ldots, M-1 \quad . \tag{6}$$

The energy eigenvector $|\phi_{n\sigma}\rangle$ and the corresponding eigenvalue $E_{n\sigma}$ are determined by

$$H|\phi_{n\sigma}\rangle = E_{n\sigma}|\phi_{n\sigma}\rangle \tag{7a}$$

$$|\phi_{n\sigma}> = \sum_{i=1}^{M} C^{\sigma}_{i,n+M-1}|i,n+M-i> \quad . \tag{7b}$$

The subscript σ in (7a) labels the eigenstates in the subspace in question.

If the atom is assumed to be initially in the M-th level, then for all time $t > 0$ the system can only be found in subspaces with $n \geq M$. There are M eigenstates of the type (7b) in every subspace. Hence the orthornormality condition is

$$\sum_{i=1}^{M} C^{\sigma'}_{i,n+M-i} \, C^{\sigma}_{i,n+M-i} = \delta_{\sigma'\sigma} \quad , \tag{8}$$

and the completeness relation is

$$\sum_{n=0}^{\infty} \sum_{\sigma=1}^{M} |\phi_{n\sigma}><\phi_{n\sigma}| = 1 \quad . \tag{9}$$

We can now solve the equation of motion for the density matrix. The reason why we use the density matrix instead of the state vector formulation is that it is easier for this to be generalized to treat the complicated problem of a mixed atomic initial state, which we shall study next. Besides, once the Hamiltonian H has been diagonalized, the elements of the density matrix can be obtained in a straightforward fashion without any increase in complexity. In fact, even if one uses the state vectors, one still has to diagonalize H. A density matrix element between energy eigenstates satisfies the equation

$$\frac{\partial}{\partial t}\rho_{n\sigma,n'\sigma'}(t) = -\frac{i}{\hbar}(E_{n\sigma}-E_{n'\sigma'})\rho_{n\sigma,n'\sigma'} \quad , \tag{10}$$

whose solution can be put in the form

$$\rho_{n\sigma,n'\sigma'}(t) = \rho_{n\sigma,n'\sigma'}(0)\, e^{-\frac{i}{\hbar}(E_{n\sigma}-E_{n'\sigma'})t} \quad . \tag{11}$$

The initial matrix element in (11) is given by

$$\rho_{n\sigma,n'\sigma'}(0) = \rho_{nn'}\,(C^{-1})^{M}_{\sigma,n+M-\sigma}\,(C^{-1})^{M}_{\sigma',n'+M-\sigma'} \quad , \tag{12}$$

where C^{-1} is the inverse matrix of the transformation defined in (4) and $\rho_{nn'}$ is the initial density matrix element of the field. The last step is from the inverse transformation of (7b), namely,

$$|n,M\rangle = \sum_{\sigma=1}^{M} (C^{-1})^{M}_{\sigma,n+M-\sigma}|\phi_{n\sigma}\rangle \quad . \tag{13}$$

If the initial density matrix is known, the mean values of all dynamical variables of the atom-field system can be calculated. The mean occupation probability of the j-th level is

$$P_j = \mathrm{Tr}(\rho A_j^{\dagger}A_j) = \sum_{n\sigma}\sum_{n'\sigma'} \rho_{n\sigma,n'\sigma'}\langle\phi_{n'\sigma'}|A_j^{\dagger}A_j|\phi_{n\sigma}\rangle$$

$$= \sum_{n,\sigma,\sigma'} \rho_{n\sigma,n\sigma'}(0)\, C^{\sigma}_{j,n+M-j}\, C^{\sigma'}_{j,n+M-j}\, \cos\{(E_{n\sigma}-E_{n\sigma'})t\} \quad . \tag{14}$$

It is easily verified that

$$\sum_{j=1}^{M} P_j = \sum_{n,\sigma,\sigma'} \rho_{n\sigma,n\sigma'} \sum_j C^{\sigma}_{j,n+M-j} C^{\sigma'}_{j,n+M-j} = \sum_{n,\sigma} \rho_{n\sigma,n\sigma} = 1 \quad , \qquad (15)$$

where we have made use of (8) and (9).

As usual, we introduce the slowly-varying complex amplitudes for the field,

$$d_1 = \frac{1}{2}[ae^{i(\Omega t-\phi)} + a^\dagger e^{-i(\Omega t-\phi)}] \quad , \qquad (16a)$$

$$d_2 = \frac{1}{2i}[ae^{i(\Omega t-\phi)} - a^\dagger e^{-i(\Omega t-\phi)}] \quad . \qquad (16b)$$

These operators satisfy the commutation relation

$$[d_1,d_2] = \frac{i}{2} \quad . \qquad (17)$$

For simplicity, in this paper we only consider the case of $\phi = 0$, for which maximum squeezing is expected, at least for the case where the atom starts in a definite state (Meystre and Zubairy 1982). The corresponding expressions for the fluctuations are then

$$(\Delta d_1)^2 = \frac{1}{4}[2\langle a^\dagger a\rangle + 1 + \langle a^2\rangle e^{2i\Omega t} + \langle a^{\dagger 2}\rangle e^{-2i\Omega t} - \langle ae^{i\Omega t} + a^\dagger e^{-i\Omega t}\rangle^2] \qquad (18a)$$

$$(\Delta d_2)^2 = \frac{1}{4}[2\langle a^\dagger a\rangle + 1 - \langle a^2\rangle e^{2i\Omega t} - \langle a^{\dagger 2}\rangle e^{-2i\Omega t}$$

$$+ \langle ae^{i\Omega t} - a^\dagger e^{-i\Omega t}\rangle^2] \quad , \tag{18b}$$

where

$$\langle a^\dagger a\rangle = \mathrm{Tr}\langle \rho a^\dagger a\rangle = \sum_{n\sigma}\sum_{n'\sigma'} \rho_{n\sigma,n'\sigma'}\langle \phi_{n'\sigma'}|a^\dagger a|\phi_{n\sigma}\rangle$$

$$= \sum_{n,j} (n+M-j) \sum_{\sigma\sigma'} \rho_{n\sigma,n'\sigma}(0)\, C^{\sigma}_{j,n+M-j}\, C^{\sigma'}_{j,n+M-j}\, \cos\{E_{n\sigma}-E_{n\sigma'},)t\} \quad , \tag{19}$$

$$\langle ae^{i\Omega t} + a^\dagger e^{-i\Omega t}\rangle = \mathrm{Tr}[\rho(ae^{i\Omega t} + a^\dagger e^{-i\Omega t})]$$

$$= 2\sum_{n}\sum_{i} \sqrt{n+M-i+1} \sum_{\sigma,\sigma'} C^{\sigma}_{n+M-i,i}\, C^{\sigma'}_{n+M-i+1,i}\, \rho_{n\sigma,(n+1)\sigma'}(0)$$

$$\times \cos[(\frac{E_{n\sigma} - E_{(n+1)\sigma'}}{\hbar} + \Omega)t] \quad , \tag{20a}$$

$$\langle ae^{i\Omega t} - a^\dagger e^{-i\Omega t}\rangle = \mathrm{Tr}[\rho(ae^{i\Omega t} - a^\dagger e^{-i\Omega t})]$$

$$= 2i\sum_{n}\sum_{i} \sqrt{n+M+1-i} \sum_{\sigma,\sigma'} C^{\sigma}_{n+M-i,i}\, C^{\sigma'}_{n+M-i+1,i}$$

$$\times \rho_{n\sigma,(n+1)\sigma'}(0)\, \sin[(\frac{E_{n\sigma} - E_{(n+1)\sigma'}}{\hbar} + \Omega)t] \tag{20b}$$

$$\langle a^2 e^{2i\Omega t} + a^{\dagger 2} e^{-2i\Omega t}\rangle = \mathrm{Tr}[\rho(a^2 e^{2i\Omega t} + a^{\dagger 2} e^{-2i\Omega t})]$$

$$= 2\sum_{n}\sum_{i} \sqrt{(n+M-i+1)(n+M-i+2)} \sum_{\sigma,\sigma'} C^{\sigma}_{n+M-i,i}$$

$$\times C^{\sigma'}_{n+M-i+2,i}\,\rho_{n\sigma,(n+2)\sigma'}(0)\,\cos[(\frac{E_{n\sigma}-E_{(n+2)\sigma'}}{\hbar}+2\Omega)t] \quad . \tag{20c}$$

They satisfy the uncertainty relation

$$\Delta d_1 \cdot \Delta d_2 \geq \frac{1}{4} \quad . \tag{21}$$

When either of them satisfy the condition

$$(\Delta d_i)^2 < \frac{1}{4} \quad , \qquad i = 1, 2 \tag{22}$$

we say that the field is in a squeezed state.

For a given n, Eq. (5) can be solved for the energy eigenvalues and eigenfunctions. With the initial density matrix elements determined by (12), we can calculate the field fluctuations and occupation probabilities of any atomic level at any time $t > 0$.

III. Results and discussion

For simplicity we assume that $\lambda_1 = \lambda_2 = \ldots = \lambda_{M-1} = \lambda$ and that the resonant interaction condition is satisfied (Li and Zhu 1985, Kozierowski 1986, Li et al 1989), i.e., $\Delta_i = 0$. In our numerical calculations we take $\hbar = 1$ and employ $1/\lambda$ as the unit of time. For the initial conditions, we consider the atom to start from the uppermost level $|M\rangle$ and the field mode to be in a coherent state. Thus we have

$$\rho_{nn'} = \frac{z^{n'} z^{*n}}{\sqrt{n!n'!}}\, e^{-\bar{n}} \quad , \tag{23}$$

where $\bar{n} = |z|^2$ is the initial mean photon number.

The relation between the field squeezing and the initial field intensity $\bar{n}$ is nonlinear. For a given energy level number of a cascade atom, there exists a value of $\bar{n}$ corresponding to the strongest squeezing or the smallest $(\Delta d_1)^2$ (Zhu et al 1988), which hereafter is referred to as $(\Delta d_1)^2_{min}$. The maximum squeezing corresponding to different level number M for some cases can be seen from Fig. 2. Some of the results are summarized in Table 1, from which it is observed that the field squeezing increases with the increase of the cascade level number. It is also noted that the larger the value of M, the later the field enters squeezed states and the longer it remains squeezed.

However, on the other hand, we find that there is saturation. For example, when M changes from 2 to 3, $(\Delta d_1)^2_{min}$ decreases from 0.2023 to 0.1730; when M changes from 8 to 10, $(\Delta d_1)^2_{min}$ decreases from 0.1309 to 0.1243; when M changes from 21 to 23, $(\Delta d_1)^2_{min}$ decreases from 0.1090 to 0.1077. Detailed behavior is shown in Fig. 3. In brief, for larger M, $(\Delta d_1)^2_{min}$ changes much less. The variance tends to saturate to some non-zero value.

Figure 4 gives an example of the time evolution of the occupation probability for the atom in the uppermost state. Comparing with Fig. 2, we can see that whenever the field enters the squeezed state from its initial coherent state, the probability of the atom lying in the uppermost state is close to its minimum. The opposite situation occurs when the field leaves the squeezed state. Thus we can conclude that squeezing effects have something to do with the absorption process, which is in agreement with the results reported by Shumovsky et al (1987).

We have discussed above the effects of the quantities M and $\bar{n}$ or z on the squeezing. As for the effects of the other quantities Δ_i and λ_i, we find

that increasing detunings Δ_i would weaken the squeezing, and there would be stronger squeezing when the coupling constants λ's are equal.

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References

Eberly J H, Narozhny N B and Sanchez-Mondragon J J 1980 Phys. Rev. Lett 44 1323

Kozierowski M 1986 J. Phys. B 19 L535

Li F L, Lin D L, George T F and Li X S 1989 Phys. Rev. A to be published

Li X S and Zhu S Y 1985 Physica A 131 579

Liu Z D, Zhu S Y and Li X S 1988 J. Mod. Opt. 35 833

Meystre P and Zubairy M S 1982 Phys. Lett. A 89 390

Puri R R and Agarwal G S 1986 Phys. Rev. A 33 3610

Savage C M 1988 Phys. Rev. Lett. 60 1828

Shumovsky A S, Kien F L and Abskenderov E I 1987 Phys. Lett. A 124 351

Table 1: Maximum squeezing under different conditions

M	$\bar{n}$	maximum squeezing
2	6	19%
4	7	36%
6	9	43%
10	11	50%
20	15	56%

Figure Captions

1. Schematic energy level diagram of the M-level atom.
2. Evolution of the variances $(\Delta d_1)^2$ (curve 1) and $(\Delta d_2)^2$ (curve 2): (a) M = 2, $\bar{n}$ = 6; (b) M = 8, $\bar{n}$ = 10; (c) M = 19, $\bar{n}$ = 15.
3. The minimum variance $(\Delta d_1)^2_{min}$ versus level number M.
4. Evolution of the highest level occupation probability P_M for M = 8 and $\bar{n}$ = 10.

Fig. 1

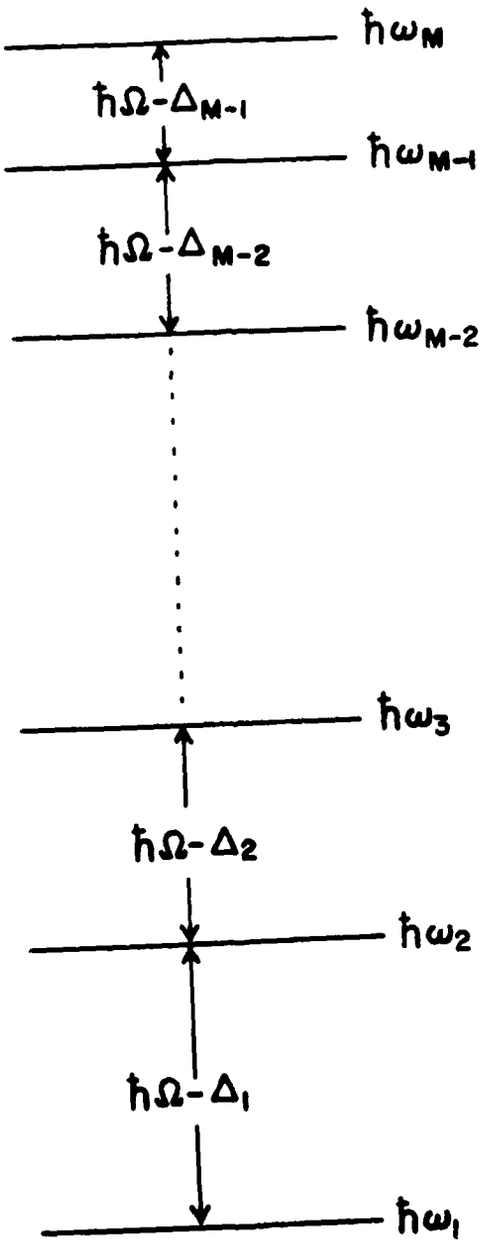

$\hbar\omega_M$
$\hbar\Omega-\Delta_{M-1}$
$\hbar\omega_{M-1}$
$\hbar\Omega-\Delta_{M-2}$
$\hbar\omega_{M-2}$
$\hbar\omega_3$
$\hbar\Omega-\Delta_2$
$\hbar\omega_2$
$\hbar\Omega-\Delta_1$
$\hbar\omega_1$

Fig. 2(a)

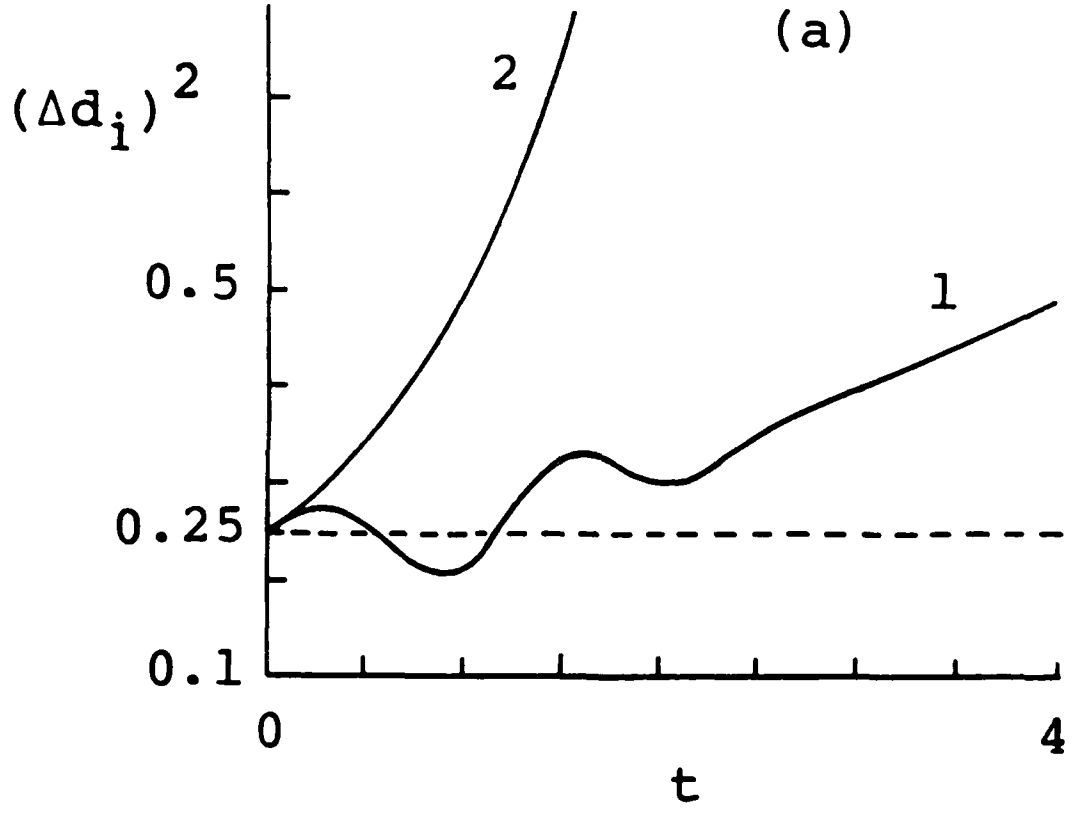


Fig. 2(b)

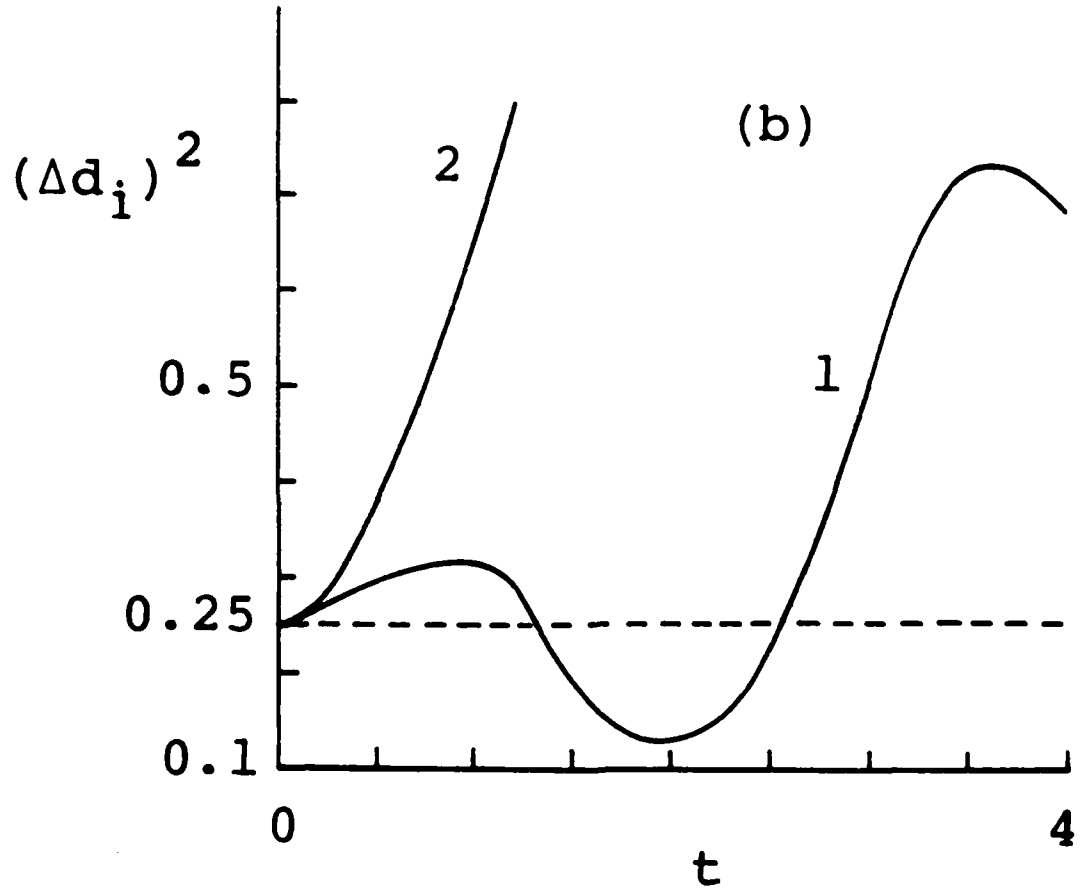


Fig. 2(c)

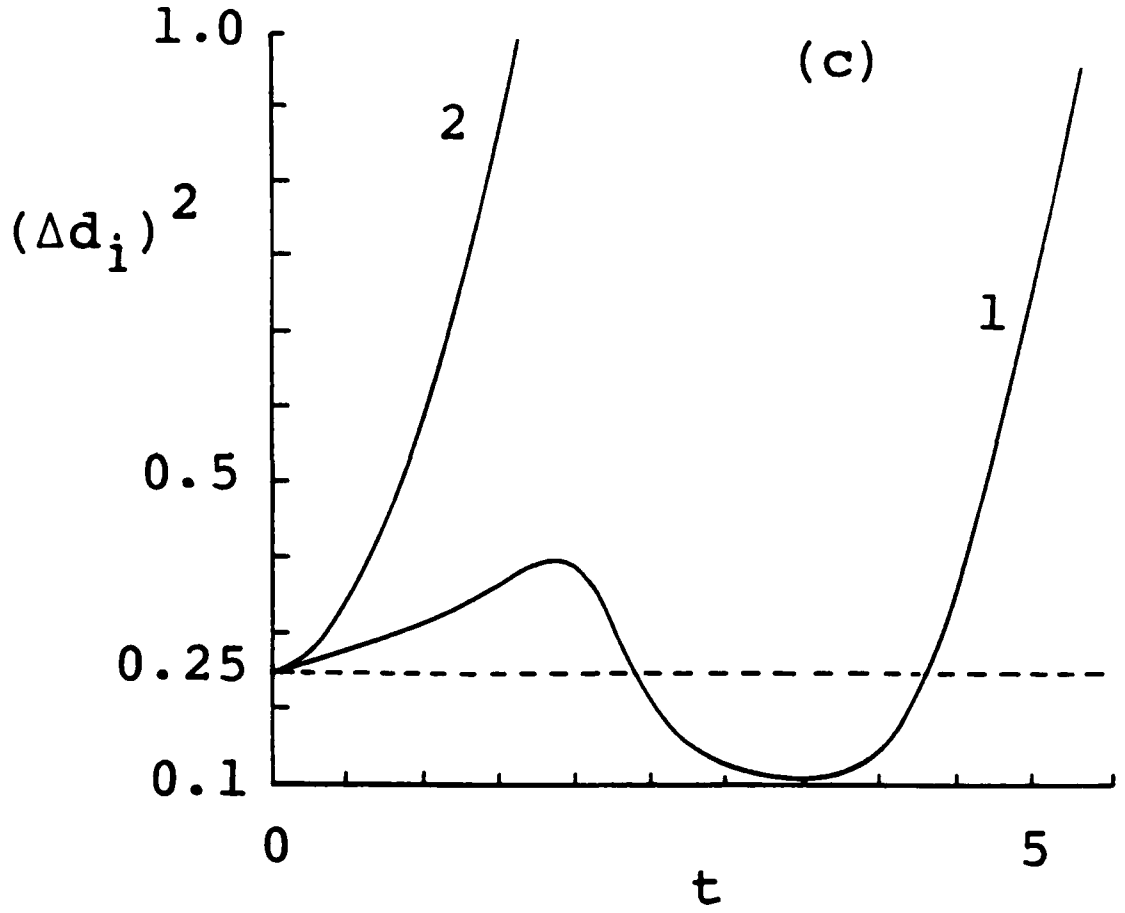


Fig. 3

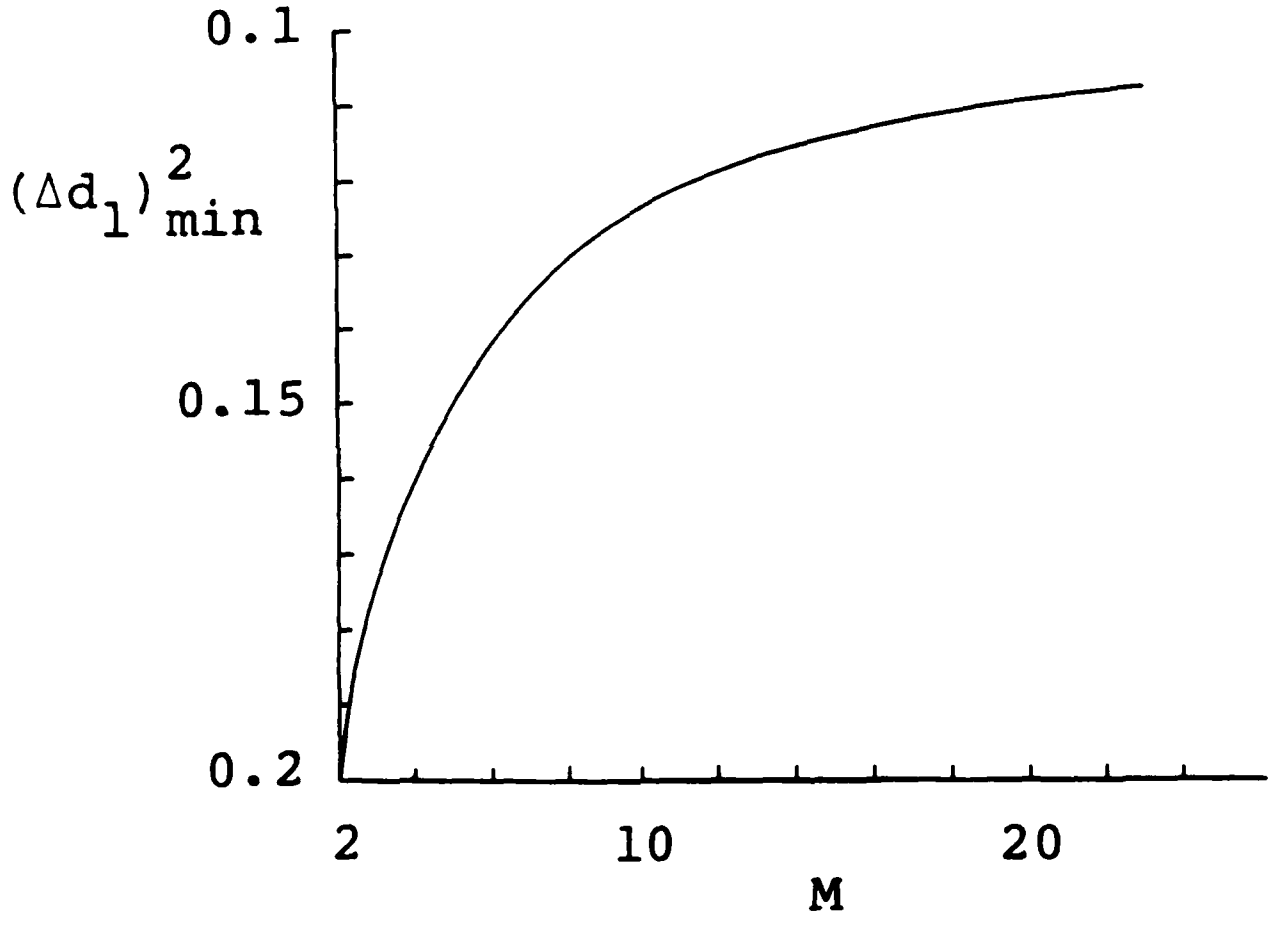
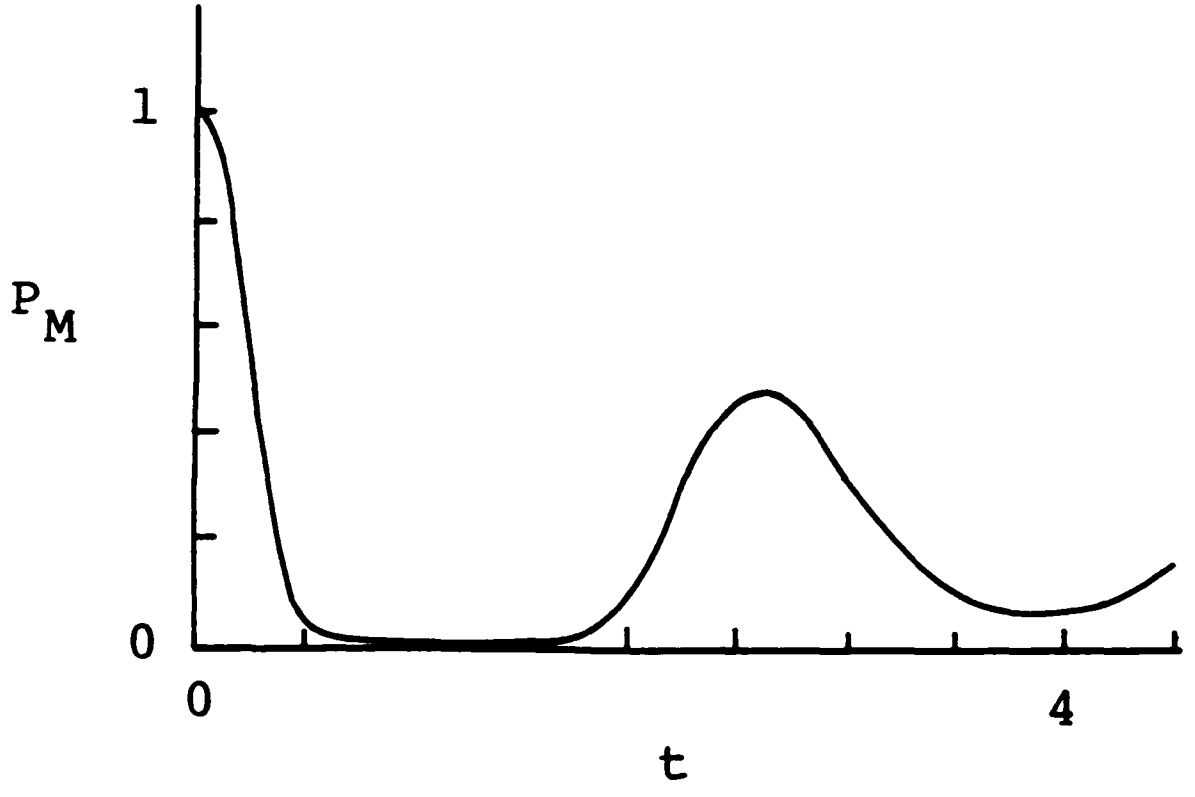


Fig. 4



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